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# The present and future of additive manufacturing in the aerospace sector: A review of important aspects

**Adrián Uriondo, Manuel Esperon-Miguez and Suresh Perinpanayagam**

**Abstract**

This paper reviews recent improvements in additive manufacturing technologies, focusing on those which have the potential to produce and repair metal parts for the aerospace industry. Electron beam melting, selective laser melting and other metal deposition processes, such as wire and arc additive manufacturing, are presently regarded as the best candidates to achieve this challenge. For this purpose, it is crucial that these technologies are well characterised and modelled to predict the resultant microstructure and mechanical properties of the part. This paper presents the state of the art in additive manufacturing and material modelling. While these processes present many advantages to the aerospace industry in comparison with traditional manufacturing processes, airworthiness and air transport safety must be guaranteed. The impact of this regulatory framework on the implementation of additive manufacturing for repair and production of parts for the aerospace industry is presented.

**Keywords**

Additive manufacturing, rapid prototyping, rapid manufacturing, process modelling, selective laser melting, electron beam melting, laser cladding, microstructure, mechanical properties, certification

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## Introduction

During the last few decades, the manufacturing industry has developed new techniques and technologies for low-volume production of innovative, customised and sustainable products with a high level of complexity and technical requirements. One of these emerging technologies is additive manufacturing (AM). According to the ASTM Standard F2729-12 a, AM can be defined as 'the process of joining materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing methodologies, such as traditional machining'.[1] For many years, this technology has been used to manufacture prototypes, but improvements in the accuracy of the process and materials' properties have allowed some industries to build parts for direct assembly purposes, such as air-cooling ducts for aircrafts[2] or hearing aids and prosthesis.[3] Rapid prototyping (RP) is a synonym for AM that is common in the literature about AM.[4] However, some authors, including Gibson et al., suggest that this term can be inadequate and does not describe the scope of this technology because it has been involved in testing, manufacturing, tooling and other activities outside of the 'prototyping' definition.[5] The ASTM Standard F2729-12 a defines RP as 'additive manufacturing of a design, often iterative, for form, fit, or functional testing, or combination thereof'.[1] Other synonyms widely used for AM in the literature are rapid manufacturing,[6] additive fabrication, layer manufacturing, direct digital manufacturing, free form fabrication and additive techniques, among others.

Nowadays, many layered manufacturing techniques have been developed, such as photo-polymerisation (stereolithgraphy[5,7] and its derivatives), ink-jet printing, fused deposition modelling,[8] Selective laser sintering (SLS),[9] selective laser melting (SLM),[10,11] electron beam melting (EBM),[12,13] direct metal deposition (MD),[14–16] amongst others. However, not all of them can produce metal parts. In this respect, SLS, SLM, laser metal deposition (LMD), EBM and wire and arc additive manufacturing (WAAM) are presently the most versatile processes to produce complex functional

School of Aerospace, Transport and Manufacturing, Cranfield University, Bedfordshire, UK

**Corresponding author:**
Adrián Uriondo, IVHM Centre, School of Aerospace, Transport and Manufacturing, Cranfield University, Cranfield, Bedfordshire MK43 0AL, UK.
Email: a.uriondo@cranfield.as.uk

metallic components (pure metals, alloys and metal matrix composites) to meet requirements from the aerospace,[2,17,18] defence[19] and biomedical industries.[20] Caffrey and Wohlers[21] have shown the increasing popularity of using this technology to produce metal components for industry by tracking metal-based AM machine sales by year. They recorded around 20 units sold in 2000 and close to 200 units in 2012.

Levy et al.[3] consider that the competitive position of AM for metal components relative to other conventional manufacturing processes depends on the geometrical complexity and required production quantity.

Holmstrom et al.[22] suggest the following benefits of AM methods over conventional manufacturing methods:

- No tooling is needed, reducing production ramp up time and cost.
- Small production batches are feasible and economical. Possibility for quick design changes.[22]
- Product optimisation for function (for example, optimised cooling channels[2]).
- The capability to produce complex geometries.
- Potential for simpler supply chains, shorter lead times and lower inventories.

Frazier presented specific technical challenges in AM to enhancing operational readiness and energy efficiency and reducing the total ownership cost of naval aircraft.[19]

- Machine-to-machine variability must be understood and controlled. Industry specifications and standards for the processing of aerospace alloy components must be developed. To achieve this goal, he suggests giving high priority to developing integrated processes, sensing monitoring and control technologies.
- Alternatives to conventional qualification methods must be found based upon validated models, probabilistic methods and part similarities among others. New standards and advanced non-destructive techniques (NDT) capable of detecting critical defects with a high degree of certainty are needed.
- New design guidelines with innovative structural characteristics are needed in order to reduce weight components.
- Physics-based models are needed in order to predict microstructure characteristics, mechanical and electrochemical properties. New alloys should be developed to optimise the process and the final properties. An understanding of how to achieve better fatigue properties and surface finish must be developed.

The purpose of this article is to review the state of the art in most extended AM technologies for metal parts, with particular emphasis on the relationship between material, process and metallurgical mechanisms.[23] A good knowledge of this field will help to develop new certification and quality assessment/quality management (QA/QM) processes for these technologies in the aerospace industry, one of the main objectives in the next few years.[19]

## Classification of AM for metal parts

Each AM technology has its particular characteristics in terms of usable material, processing procedures and capabilities. Nevertheless, most of them work using a point-wise method and use metal powder as a raw material. Companies, like Solidica in the US, use an ultrasonic consolidation process to produce parts.[24] In this review, only SLM, EBM, LMD and WAAM are considered and described because they are presently regarded as the four AM processes most applicable to the aerospace industry and because they can produce almost fully dense components without any post-processes (close to 99.9% density[11,20,25,26]) with mechanical and electrochemical properties comparable to other traditional methods.

There are many ways to classify these technologies. Figure 1 shows a diagram where these technologies are classified according to the mechanism of pre-spreading the raw material. On the one hand, powder bed fusion process technologies have one or more thermal sources to melt the powder, a method to control the powder fusion to a specific region in each layer and a mechanism to pre-spread a smooth powder layer. On the other hand, MD processes are those that melt the material as it is being put down.

Both SLM and LMD use a high-power laser. However, EBM uses an electron beam and WAAM, a plasma arc.

Laser technology[27,28] has improved in recent years in terms of small focused spots, higher laser power and wavelengths better tuned to the absorptivity of metal powder.[27,29,30] Nowadays, almost all AM laser machines use fibre lasers instead of $CO_2$ lasers or Nd:YAG.

The following section provides a summary of the main characteristics of SLM, EBM and LMD, and which is the currently capability to obtain high-performance components according to the various mechanisms of beam energy–powder interaction (e.g. pre-spreading powder in a powder bed before laser scanning[31] or coaxial feeding of powder by nozzle with synchronous laser scanning[8,16]), deposition rate, processing conditions, material and scan strategy amongst others.

Finally, it is important to note that the terminology for SLM, EBM and LMD technologies varies across organisations and institutions (Table 1).

### *Electron beam melting*

EBM uses a high-energy electron beam to heat and melt the metal powder. This process uses the same

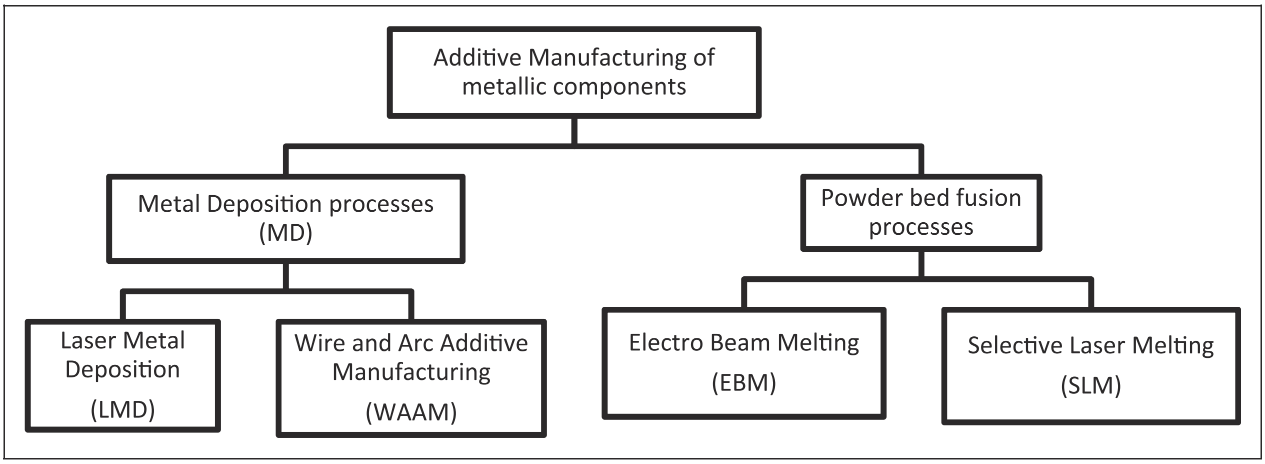


**Figure 1.** Classification of AM processes based on energy source and powder delivery system.

**Table 1.** Nomenclature for SLM, EBM and LMD.[20]

| Processes | Synonyms from different institutions/firms |
|---|---|
| SLM | *Direct metal laser sintering* (EOS GmbH, Germany) |
| | *Direct metal laser re-melting* (University of Liverpool, UK) |
| | *Lasercusing* (Sauer Product GmbH, Germany) |
| LMD | *Direct metal deposition* (University of Michigan, USA) |
| | *Laser engineered net shaping* (Sandia National Laboratory, USA) |
| | *Directed light fabrication* (Los Alamos, USA) |
| | *Direct laser deposition* (University of Manchester, UK) |
| | *Direct laser fabrication* (University of Birmingham) |
| | *Laser rapid forming* (North-Western Polytechnical University and Hong Kong Polytechnic University, China) |
| | *Laser melting deposition* (Beihang University, China) |
| EBM | *Electron beam melting* (Arcam, Sweden) |

EBM: electron beam melting; SLM: selective laser melting; LMD: laser metal deposition.

principles as electron beam welding.[32] This technology is mainly commercialised by Arcam.[33] As shown in Figure 2(a), the electron beam is generated and then accelerated in a heated filament (1) with a voltage difference of around 60 kV.[5,34] This system is typically more efficient than a laser beam generator because most of the energy is converted into the electron beam and higher beam energies are available with less cost.

Electrons move close to the speed of light (around 70%[34]) and, as in electron beam welding, the process has to be carried out in a vacuum, so that electrons do not interact with the atoms of the atmosphere and are not reflected.

The powder is normally fed by gravity from the cassettes (4) and distributed (5) onto the built platform (7). The beam is focused with a focus coiling (2) in order to achieve the correct spot diameter and electromagnetically positioned (3) with deflection coils that control x–y motion. The building direction (z axis) is denoted by the arrow (B).

## *Selective laser melting*

SLM (Figure 2b) uses a high-energy laser beam (1) to heat and melt the metal powder (layers $\sim$0.1 mm thick[5]) which has been racked across the build area (5) using a counter-rotating powder levelling roller (4). The powder is fed from a container (6). The powder that is not used can be recycled (7). After finishing a layer, the build platform is lowered by one layer thickness and a new powder bed is spread. The building process takes place in a protected atmosphere (normally argon or nitrogen gas) to minimise the oxidation and degradation of the material during the process. This technology uses galvanometers (2) (mirrors) to control the position of the laser spot. The building direction (z axis) is denoted by the arrow (B).

## *Comparison of electron and laser beam melting*

Both systems create a powder bed by raking or rolling powder from cassettes into a compacted layer. However, the inherent characteristics of the heat source in each process affect the material being processed. Whilst in SLM the energy of the photons is absorbed by the powder particles, in EBM the electrons transfer their kinetic energy to the powder particles.[30,35] This means that the powder particles increase their negative charge. If the conductivity of the raw material is not high enough to avoid the negative charge[5]:

- The electronegativity of the powder bed will create a more diffuse beam due to tendency of the charged powder to repel the incoming electrons; and
- if the order of magnitude of the repulsive force is close or superior to the order of magnitude of the

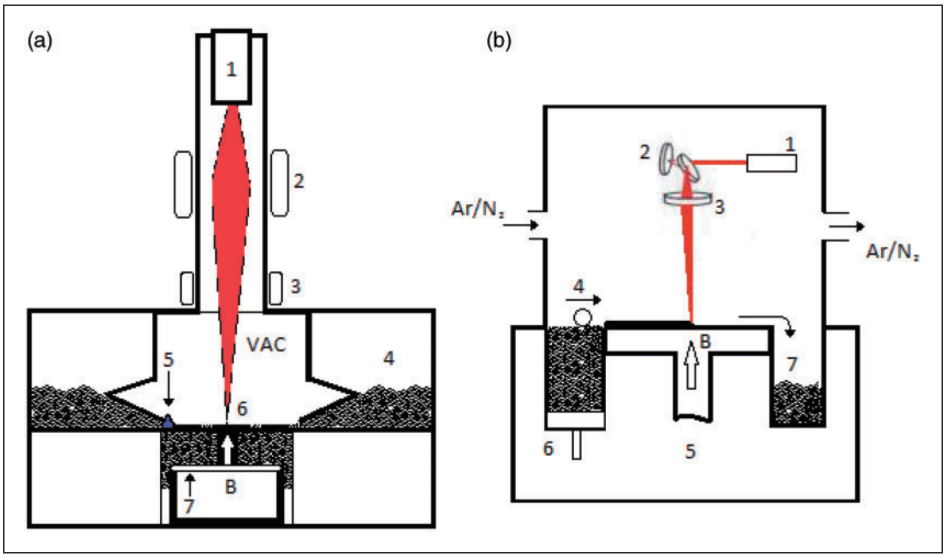


**Figure 2.** EBM (a) and SLM (b) systems schematics.

gravitational and frictional forces, there will be an expulsion of powder particles from the powder bed.

To avoid these problems, the conductivity of the raw material must be high. This means that EBM can only process materials like metals, whereas SLM can process any material that can absorb energy from a laser wavelength.

Another important issue is the energy cost. In EBM, most of the energy applied to the heated filament to generate the beam is converted into the electron's kinetic energy but in SLM, only 10–20% of the total energy input is converted into the laser beam.[5] However, fibre lasers have better energy conversion efficiency (around 70–80% for some cases).[5,27] Consequently, this might not be a major advantage of EBM over SLM.

In both EBM and SLM, the powder bed is maintained at an elevated temperature. Pre-heating the powder is necessary to minimise the laser/electron beam power requirements and to prevent the part form warping due to high thermal gradient (curling).[36–39] However, there is a difference between both heating mechanisms and the operating temperatures of both processes.

SLM: Infrared heaters placed above the build chamber maintain the temperature of the powder bed around 90°C.[40]

EBM: Defocusing the electron beam and scanning the powder bed very quickly over the total surface heats the powder bed before placing the next layer to a uniform pre-set temperature (close to the melting point).[40]

Furthermore, the inert atmosphere present in SLM processes in the build chamber favours heat conduction. All these characteristics result in the cooling rate of the melted pool in SLM creating smaller grain sizes.

As a result, the microstructure of the part changes significantly from EBM to SLM and thus, the mechanical properties will be different.[13,41,42]

### *Metal Deposition processes*

Unlike in powder bed fusion processes, in MD processes, the raw material is melted as it is being deposited in the form of a powder[43] or wire[37] feedstock. Most of those technologies use a laser as a heat source, but there are similar processes that use an electron beam or a plasma source instead of a laser beam as a heat source.[15,37,44,45] The deposition head is usually an integrated collection of a heat source, a powder nozzle(s) and inert gas, like in Laser Cladding (LC). The powder is focused at the melting pool using either co-axial feeding,[46] four-nozzle feeding or single-nozzle feeding. MD processes involve deposition, melting and solidification of raw material in a moving melt pool. Thus, the final parts can achieve an elevated density during the process, being the higher porosity level close to the surface of the part.[5,14,43] The typical microstructure attained is similar to that in the SLM process due to the high cooling rates (from $10^3$ C/s to as high as $10^4$ C/s).[47,48]

Residual stresses are one of the most significant problems in MD processes.[5] They are generated as a result of this solidification, which can lead to cracking during or after part construction.

This technology can repair components which have been considered non-repairable by conventional methods.[49] European projects, including FANTASIA[50] and TurPro[51], have demonstrated the potential of this technology for repair of high-valued turbo-engine components.

### Conclusions

There are a large number of AM technologies that can produce metal components, but not all of them can achieve the same quality of the final part. EBM, SLM and some MD processes look to be the most applicable technologies for high technical requirement parts. The development of physics-based models to correlate microstructure-property-processing variables to the size/type of defect is essential in order to produce AM parts consistently and accurately.

## Aerospace alloys in AM processes

There are various alloys for AM technologies. A majority of research efforts have focused on Ti-,[52] Ni-[25] and Fe-based alloys. Only Ti- and Ni-based alloys are discussed here due to their importance in aerospace applications. A review of these alloys is presented in Table 2.

### Titanium alloys

Facchini et al.[54,55] have studied how to modify the mechanical properties of Ti6Al4V AM parts with heat treatments. They improved the ductility of the material by modifying the metastable martensite into a biphasic α-phase acicular microstructure. This suggests how to control the martensite transformation of Ti6Al4V alloy through the variation of AM parameters. Due to the cooling rate being higher for SLM than EBM, the resultant microstructure of Ti6Al4V components differ from dominant martensite to fine α-phase structure, respectively.[56] This means that the hardness and the ductility will be different for the two processes. Murr et al.[40] studied the microstructure differences for Ti6Al4V concluding that the hardness in SLM (41 HRC) is greater than in EBM (32 HRC) for Ti6Al4V components. They do not observe any main directional grain grow for both processes. However, Thijs et al.[26] have concluded that for SLM processes, the orientation of the grains is highly dependent on the scan velocity and scan strategy. They suggest controlling the grain orientation during the process with the scan strategy. The analysis of transmission electron microscopy images from the studies of Murr et al.[40,52] show high dislocation density inside α-phase grains in EBM processes and deformation twins in α-phase in the martensitic structure (see Figure 3). This deformation is a consequence of the rapid cooling rate of both processes and indicates a high level of induced thermal residual stresses. Also, due to the high cooling rate and high conductive heat transfer rate in both processes, only a small volume of precipitates ($Ti_3Al$) will be formed. Thijs et al.[26] observed in their studies that if more material remains at a higher temperature for a longer time, the volume of precipitates will increase and consequently, the micro-hardness will be higher.[26] To achieve this goal, they present two alternatives: lowering the hatch spacing or the scanning velocity.

Vrancken et al.[57] studied the influence of mixing Ti6Al4V ELI powder with 10 wt.% Mo powder.[57] The mixed powder was processed by an SLM machine. The resulting microstructure consisted of homogenously dispersed Mo particles in a β-phase matrix with a <100> cube texture in the building direction. It presented a high strength ($\sigma_{0.2} = 858$ MPa) and excellent ductility (A = 21). Table 3 summarises the mechanical properties of EBM Ti6Al4V specimens.

### Nickel alloys

Nickel-based alloys are used for high-performance components in the aerospace industry due to their tensile properties, damage tolerance, ability to creep at high temperature and corrosion/oxidation resistance.[60] Those alloys are strengthened by precipitates. However, AM processes result in a high cracking tendency due to the amount of elements in the intermetallic phases. With these alloys, it is difficult to eliminate all the short cracks merely by adjusting the process parameters of the machine. A Hot Isostatic Pressing (HIP) process is required to improve the mechanical properties. Static mechanical properties of Inconel 625 processed by EBM (ARCAM™) are presented in Table 4. Before HIP, the microstructure was characterised by columnar

**Table 2.** Alloys for various AM processes.

| Based elements | Alloys | Powder characteristics | References |
|---|---|---|---|
| Ti | Ti6Al4V | Particle size 25–45 μm | Gu et al.[20] |
| | Ti6Al4V ELI | Particle size 25–45 μm | Gu et al.[20] |
| Ni | Inconel 625 | Spherical shape (95%); particle size 20–135 μm | Gu et al.[20] |
| | Waspaloy | Average particle size 63 μm | Gu et al.[20] |
| | Inconel 718 | Particle size 44–150 μm | Gu et al.[20] |
| | Rene 88DT | Particle size 44–150 μm | Gu et al.[20] |
| | Rene 41 | Atomised with Ar | Gu et al.[20] |
| | HastelloyX | Particles size 20 μm | Brodin et al.[53] |

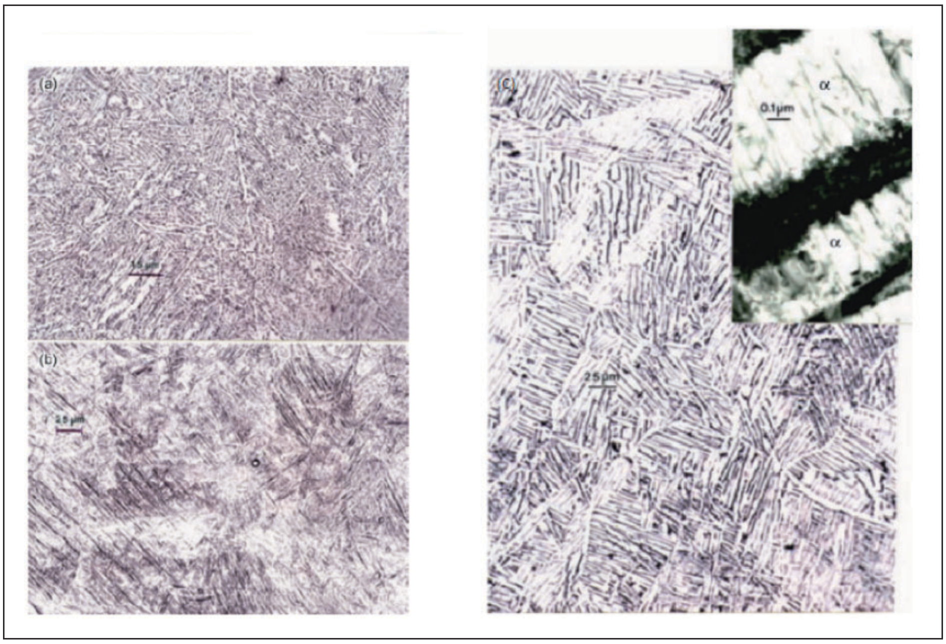


**Figure 3.** (a) Ti6Al4V fabricated by EBM. (b) Ti6Al4V fabricated by SLM. (c) The TEM image for EBM-fabricated Ti6Al4V shows high dislocation density in α-phase.[40]

**Table 3.** Static mechanical properties of Ti6Al4V without any post-process in the build direction.

| Process | Yield strength (YS) [GPa] | Ultimate tensile strength (UTS) [GPa] | % Elongation | References |
|---|---|---|---|---|
| EBM | 1.1–1.15 | 1.15–1.2 | 16–25 | Murr et al. [13] |
| | 0.83 | 0.915 | – | Facchini et al.[55] |
| | 0.735 | 0.775 | 2.3 | Koike et al.[58] |
| SLM | 0.865 | 0.972 | 10 | SLM solutions (GmbH) |
| | 1.07 | 1.2 | 11 | EOS (GmbH) |
| | 0.835 | 0.915 | 10.6 | Facchini et al.[54] |
| | 0.99 | 1.095 | 8.1 | Facchini et al.[54] |
| WAAM | 803 | 918 | – | Ding and Williams[59] |

EBM: electron beam melting; SLM: selective laser melting; WAAM: wire and arc additive manufacturing.

**Table 4.** Static mechanical properties of IN645 achieved by EBM.

| Process | YS [MPa] | UTS [MPa] | % Elongation |
|---|---|---|---|
| EBM | 410 | 750 | 44 |
| EBM + HIP | 330 | 770 | 69 |

The HIP process conditions applied were at 1393 K, 100 MPa for 4 h.[25]
EBM: electron beam melting.

grains (up to 20 μm). Subsequently, the columnar grains recrystallised, and the metastable γ′-phase ($Ni_3Nb$) becomes dissolved. Murr et al.,[25] due to unusual microstructures achieved in their studies, suggest the possibility of designing the microstructure of the part modifying process parameters during the process.

**Table 5.** Static mechanical properties of IN718 for SLM and EBM.[62]

| AM process | YS [MPa] | UTS [MPa] | % Elongation |
|---|---|---|---|
| EBM | 580 | 910 | 22 |
| SLM | 552 | 904 | 16 |

EBM: electron beam melting; AM: additive manufacturing; SLM: selective laser melting.

Strondl et al.[61] have studied the microstructure and phases of Inconel 718 with EBM (ARCAM$^{TM}$) without any post-process. They obtained a matrix consisting of γ-phase grains oriented in almost the same direction, like a single crystal. The precipitates are aligned following the grow direction of each grain. Mechanical properties of this alloy in various AM technologies are reported in Table 5.

### Fatigue, porosity, and roughness

Roughness and porosity are the main factors that affect fatigue behaviour directly. It is very important to identify the influence of both parameters in this failure mechanism. Chan et al.[63] investigated the effect of roughness on fatigue life in Ti6Al4V parts fabricated by EBM (ARCAM A2, ARCAM$^{TM}$) and SLM (EOSINT M270, EOS GmbH). They concluded that the fatigue life of SLM parts is higher than that of EBM. They correlated the fatigue life in cycles with the surface finish, concluding that a high level of roughness results in a shorter fatigue life. Greitemeir et al.[64] showed that the surface defects had the most pronounced impact on reducing high cycle fatigue life.[64]

The porosity level is less important than the microstructure of the alloy (HIP processes to avoid porosity do not have a significant impact on fatigue life).

Surface roughness depends on the technology, the scan strategy, the position of the part on the build platform, and some other process parameters, like the hatch space or the scan velocity.[26,62] Mazumder et al.[65] showed that for laser cladding, a type of MD process, the largest roughness can be measured perpendicular to the clad direction on the top surface (5% greater than in the parallel direction) and in the vertical direction on the walls (3% greater than in the horizontal direction).

### Conclusions

For each alloy and technology, it is possible to fix a set of process parameters in AM to achieve static mechanical properties close to those obtained by traditional technologies. The high cooling rates during AM processes produce small grain size. This increases the crack incubation period resulting in better fatigue properties at low temperature. The surface finish dominates the fatigue behaviour rather than the porosity.

However, AM parts present a strong anisotropy due to the characteristics of the process itself. Normally, the building direction (Z-direction)[66] is the weakest in terms of the ultimate tensile stress.[62]

Ti6Al4V is the most widely alloy used in AM technologies. However, other materials like steel- and Ni-based alloys, amongst others, have increased in popularity in the aerospace industry. Further studies in terms of metallurgical mechanisms during AM are required to fit a successful AM application. The number of powder-based alloys should be extended in order to achieve more applicable materials to different situations.

AM offers the possibility of creating 'designed material' with characteristics which do not exist.[20] To effectively use AM in the aerospace industry, it is necessary to have models that correlate the final part's characteristics with process variables.

## Modelling AM processes

Certifying AM parts for aerospace applications requires a better control of the machines as well as good process-microstructural models to predict the final properties of each part.[4,19] This can be monitored via process variables, such as laser power, scan velocity, preheating temperatures and scan strategy, among others (Figure 4). Wide experience in welding processes and other manufacturing methods has demonstrated that both the temperature distribution as well as the temperature history have an influence on the distortion induced by residual stresses, microstructure and consequently, on the fatigue behaviour. Much research related to the analysis of temperature distribution in transient heat conduction for welding[67] have been applied to modelling AM processes.[68] However, none of this research takes into account all physical phenomena of the process, such as non-thermal constant properties, heat of phase transformation, natural convection in the liquid pool, latent heat of fusion, vaporisation and solidification, among others. Neglecting these effects can result in important differences between the model and actual performance. For instance, Negi et al.[36] showed with a finite element analysis (FEA) that taking into account the effect of variable material thermal properties as well as the effect of radiation and convection heat, prediction of the temperature distribution is more accurate compared with the experimental case. Zhang et al.[69] show that neglecting melting and re-solidification processes, and therefore the change of density, could result in important errors in the thermal model.

The need to maintain proper build conditions and limit residual stress is coupled with the desire to control the microstructure of the part. Process maps for each alloy and AM process have been developed to understand the relationship between process variables (laser power, scan velocity, preheating temperatures, part geometry, etc.) and relevant cooling rates to obtain desirable microstructural features.[68] These process maps are developed using non-linear thermo-mechanical finite element simulation and different testing samples.

### SLM models

SLM is a complex process with multiple physical phenomena. The laser beam interacts with the material, which at the beginning is powder, but then melts to become liquid; heat transfer depends on the conductivity and it changes from powder to dense parts, both of them being part of the interface with the molten pool; gravity forces and temperature gradients in the pool produce natural and Marangoni convections. A good understanding of the above-mentioned phenomena will allow control of the properties of the

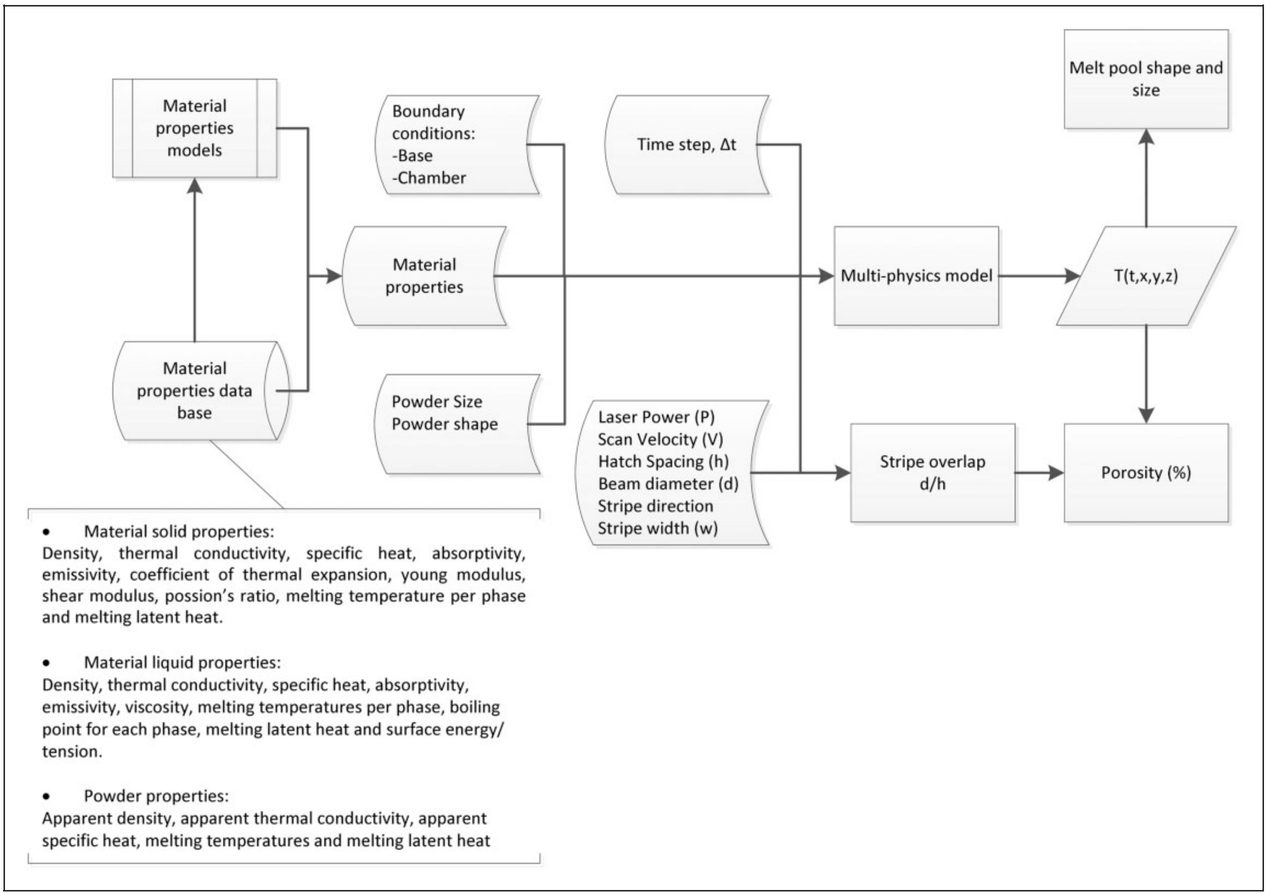


**Figure 4.** Detailed model map for a SLM process.

parts produced, such as microstructure, porosity and residual stresses.

Verhaeghe et al.[70] developed a model to study the influence of evaporation. They concluded that for high-energy density inputs, evaporation occurs and its effect in the temperature field in the pool cannot be neglected. Additionally, the depth of the pool taking into account the evaporation is smaller due to part of the input energy being used in the liquid–gas phase change. However, the size and shape of the cross-section did not agree with the experimental data. Based on the results available in the literature, it can be concluded that including the Marangoni convection in the model could help to improve the model and reproduce a more realistic melt pool width and depth.

Kobryn and co-workers[8] have studied how process variables, such as the power or the scan velocity, can have an impact on the final microstructure of Ti6Al4V for LMD or SLM. They first use an analytical model based on the Rosenthal[71] solution. This approach does not take into account the nonlinear effects of temperature-dependent properties and the latent heat of the alloy. However, it shows the order of magnitude of some process variables in thin wall and bulky structures. These results have been compared with a numerical model based on a FEA in order to study the influence of the neglected effect. They conclude that the Rosenthal results for both situations, thin wall and bulky structures, are compatible with those obtained from the numerical model (FEA) with low laser power (between 350 and 750 W).[8]

Gürtler et al.[72] used the three-dimensional (3D) volume of fluid method to study the effect of the powder-layer thickness, power, scan spacing and scan velocity on the process dynamics. In their model, they used part of the Otto and Schmidt[28] models for laser material processing. Realistic results for process dynamics and defects were achieved.

Models from other technologies close to SLM (like SLS) have been used to understand the influence of other parameters, such as the number of layers underneath. Chen and Zhang[73] concluded that the dimensionless intensity of the moving heat source in SLS processes to achieve the desired sintering depth and to bond the newly sintered layer to the previously sintered ones increases with the scanning velocity.

Xiao and Zhang[74] have also studied the influence of existing sintered layers in SLS processes, but including Marangoni and natural convections in their model. The model was validated by comparing the predicted cross-section for the liquid/solid interface during laser melting of a nonporous 6063 aluminium sheet with experimental results. They concluded that the flow has a high influence on the temperature field and consequently on the shape of the melt pool. Also, if the number of existing sintered layers underneath is increased, higher energy density is needed to achieve the required overlap between the layers and to avoid the negative 'lack of fusion' phenomena.

Several experiments have indicated that if the scan velocity falls outside a specific interval, tracks become broken. This undesirable instability in the pool during the process is known in the literature as the 'balling' effect. This phenomenon can be explained by the Plateau–Rayleigh capillary instability for high scan velocities. Gusarov et al.,[75] neglecting melt flow and therefore the Marangoni convection, created a physical model taking into account radiation and heat transfer to study this effect for high scan velocities. They concluded that this simple model can be used to estimate the contact between the melted material and the layer underneath, one of the factors that avoid 'balling'. Zhou et al.[30] suggest packing different types of metal powders with different melting points and different emissivities to avoid 'balling'.

## EBM models

The literature on models for EBM is more limited than for that for SLM or SLS. Since EBM processes use an electron beam to melt the powder, the beam–powder interaction is substantially different than in SLM or LC. The penetration depth of the beam into the powder is higher than for a laser with the same power, because electrons have their own inertia and require a large number of collisions (elastic and inelastic) until their kinetic energy is absorbed by the material. Using Monte Carlo methods, the absorption path of individual electrons can be tracked.[76] Another important aspect is that the maximum energy absorbed by the material is at a considerable distance below the surface, whereas all the energy from a laser is absorbed at the surface. Klassen et al.[35] showed the strong influence of the electron beam absorption and the depth of penetration on the quality of the part using a two-dimensional 2D-thermal lattice Boltzmann method (LBM). They also have developed a strategy to combine various semi-empirical expressions to compute the beam energy attenuation as a function of material characteristics and the incident electron energy.

Zäh and Lutzmann[29] have used a FEA model, which solves the heat conduction equation modified by the implementation of an abstracted heat source, to study the influence of beam power and scan velocity on the shape of the melt pool. They validated the model using experimental data from thermocouples attached to the build platform. However, this model has been proven for a set of process variables that ignore two of the most relevant defects in this technology: ball formation and delamination. Therefore, better models for predicting melt ball formation during EBM processes will be necessary.

Jamshidini et al.[77] applied a coupled Computational Fluid Dynamics (CFD)–FEA to study the heat and thermal stress distribution in EBM with Ti6Al4V powder. This model takes into account the fluid convection through the CFD model and combines it with the FEA to determinate the thermal stresses. They conclude that power and the cooling rate are the more relevant factors for thermal stresses, and the negative temperature coefficient of surface tension is responsible for the formation of an outward flow in the molten pool on the top surface. This effect combined with the wetting capability of the solidified layer on which new material is melted will produce the melt ball formation.

According to Gusarov et al.,[75] narrow melt pools tend to suffer from 'balling' rather than solidify as a smooth layer.

## LMD models

Due to the nature of the process, only the powder dissolved into the melt pool contributes to the manufacturing process. Systematic investigations have been carried out to improve the processing control and the final quality of the part. Due to heat generated by the laser, using sensors near the melt pool to record data is very difficult. Thus, using good models constitutes the only efficient way to predict morphologies, thermal fields, etc.

Peyre et al. proposed a combined analytical–numerical model (using COMSOL Multi-physics™ software) to predict geometries and thermal fields during LMD processes with Ti6Al4V powder. Their two main assumptions are:

- The powder arrives at an average temperature and with a local mass rate which interacts with the molten pool.
- The energy inside the pool is enough to melt the incoming powder.[78]

To validate their model, they recorded the local temperature history (thermocouples and pyrometers) and the melt pool size (fast camera). Both sets of data were compatible with simulation data for Ti6Al4V.

There is much research that has proposed transient models for LMD using FEM. Unlike the previous model, these do not use a predictive approach for wall dimension prior to calculations. Ye et al.[79] used one of these models to predict the temperature distribution for AISI 316 steel. Alimardani et al.[80] proposed a 3D-FEA model with which the shape of each layer, and the temperature and stress fields can be calculated at any time. This model includes also the Marangoni phenomenon, power attenuation, effect of angle of incidence and the effect of external forces and displacements.

They conclude that preheating the powder helps to reduce residual stresses as well as settling time for the formation of a steady-state molten pool, and clamping the workpiece at a specific position also can help to decrease residual stresses.

The material deposition in all FEA models for LMD has been modelled following one of these two strategies:

- Using quiet elements: elements are present during the analysis but with very low values of thermal conductivity and specific heat in order to reduce conduction into this region. The major advantages are that they are easy to implement in commercial finite element solvers and, since the number of elements does not change, the number of equations is constant and solver initialisation during the simulation process is not needed.
- Using inactive elements: elements are not included during the analysis until they have been added. Their major advantage is that they do not need scaling factors to minimise thermal conductivity and specific heat. However, the method cannot be easily integrated into commercial finite elements solvers.

A variety of general purpose commercial codes have used one of those strategies to model MD (Ye et al.[79] use Abaqus™ in their simulations). Michaleris[81] showed that neglecting surface convection and radiation on the interface between active and inactive elements results in artificial heating generation (more than a 5% error) and proposes a hybrid inactive/quiet method to accelerate computer run times.

Another important topic is the prediction of the morphology and size of the grain in the final part. The next section is a brief summary of mesoscopic models that can be applied to achieve this objective.

### Mesoscopic simulation

The LBM[82,83] is a mathematical model based on the Cellular Automaton (CA) theory that has been used as an alternative to ordinary fluid dynamics models, especially in problems with complex interface (e.g. flows in porous media). Körner et al.[83] developed a 2D-LBM model to study the influence of melting and solidification of a randomly packed powder bed under a Gaussian beam. Their numerical experiments have demonstrated that the packing density of the powder bed has the most significant effect on the melt pool characteristics.

CA modelling has also been used to simulate the evolution of the microstructure during the solidification process as an alternative to phase-field models[84–87] which have been used in other disciplines. For instance, Gandin et al.[88] developed a 3D CA combined with a FEA to predict the grain structure in casting processes. Such models permit estimating which values of the thermal gradient and cooling rate are needed in casting to obtain a specific grain structure (equi-axed, columnar, etc.). Kobryn and co-workers[8] calculated predictions of solidification microstructure in Ti6Al4V for SLM for thin wall and bulky 3D geometries.[8] This model has been successful in predicting the fully columnar microstructure associated with SLM at relative small scales.

### Conclusions

The prediction of the composition/microstructure and the formation of residual stresses during the process are regarded as two major difficulties in AM processes. Having good models of the process is the base to improving the process and having better quality parts. Figure 5 represents all the current different simulation areas and how they are interconnected.

There is much research that is focused on developing models for AM processes. However, all these models are incomplete due to the high complexity of the system. Developing better models of each area will result in the effective use of AM technology.

While simulations and models of thermo-mechanical processes in AM are currently being developed (there are still many challenges ahead), their coupling with fluid dynamics has not yet been well established (e.g. in transient melt pools).

From the point of view of FEA methods, improvements of the adaptive meshing strategies will have to deal with whole parts or even structures. This will result in very high computational times.

The influence of material characteristics and processing conditions on the metallurgical mechanism and resultant microstructural and mechanical properties of AM-produced parts provide us with all the information to control the process and to achieve all the technical requirements of each spare part.[25,41,42]

## Certification in the aerospace market

Implementing AM to produce and repair aerospace components (parts and tools) requires, not only being competitive against conventional manufacturing methods in terms of time and cost, but also meeting all the parts' requirements and ensuring that each aspect of its value chain can be certified. AM faces many technical challenges when compared to other conventional manufacturing processes, such as the hybrid nature of the resulting part, the complexity of the deposition system, the effect of reused powder, etc.

AM implementation in design, manufacturing and repairing stages for aerospace components must be in concordance with the corresponding competent authority to ensure aircraft airworthiness and air transport safety.

As air traffic continues to grow, a common endeavour is needed to keep air transport safe and sustainable. The European Aviation Safety Agency (EASA) and the Federal Aviation Administration are the two organisations which are responsible for standards of

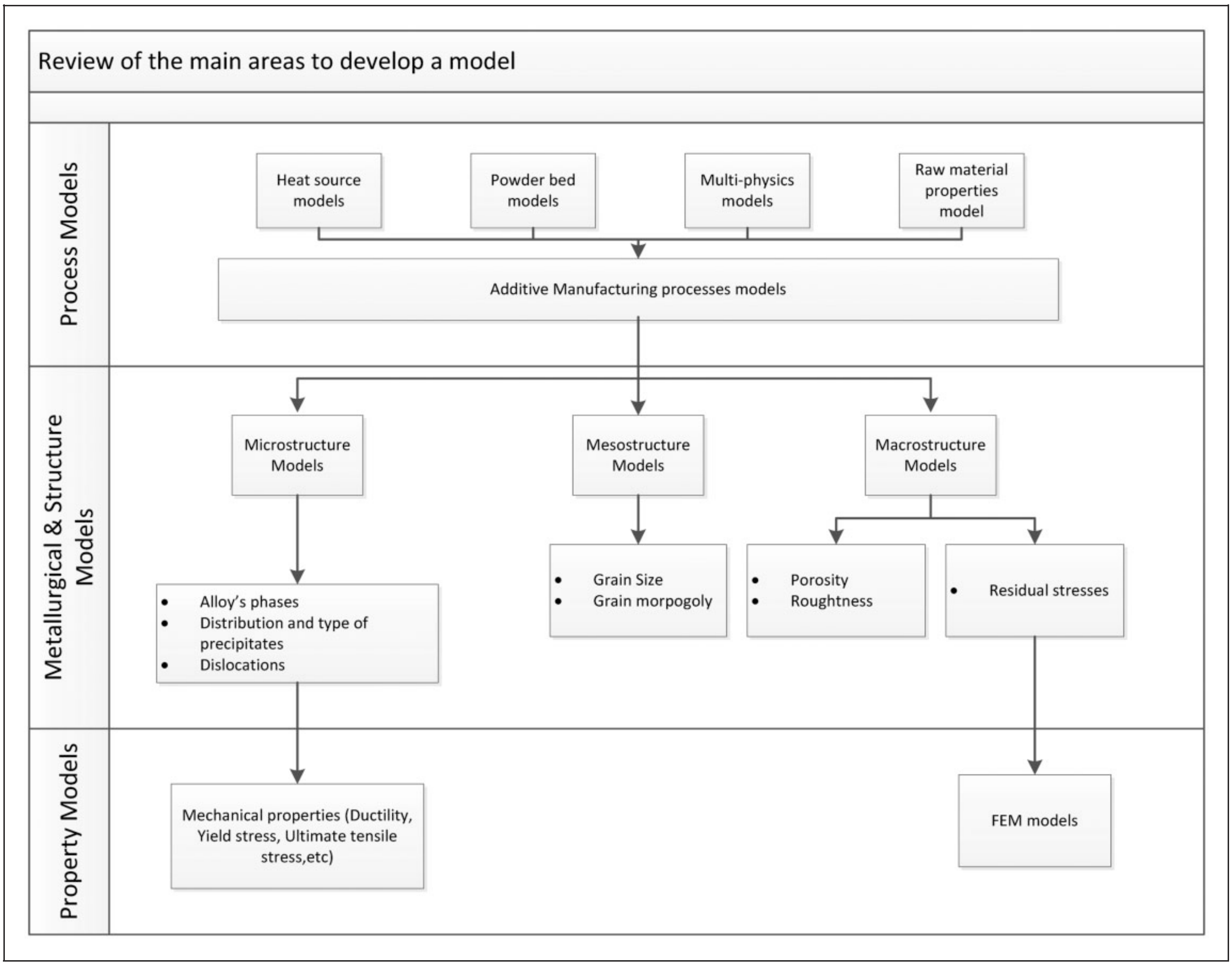


**Figure 5.** Review areas in AM modelling.

safety and environmental protection in civil aviation, not only in their region but also for those countries with which they have bilateral agreements. Regulation (EC) No. 2042/2003 has four Annexes.[89]

Annex I (Part M) focuses on all processes that ensure that an aircraft complies with airworthiness requirements in effect during its operational life and that it can be operated safely, including maintenance.[90]

Annex II (Part 145) describes the conditions have to be met for an organisation to be approved in Maintenance, Repair and Overhaul (MRO).[91] Each competent authority (a competent authority is designated by each Member State (EASA Member States are not necessarily Member States of the European Union (EU). For instance, Switzerland and Iceland are EASA Member States but are not part of the EU.) or the Agency if so requested by that Member State) shall establish procedures detailing how to comply with the Part 145, Section B.[91] These procedures must be reviewed and amended to ensure continued compliance. Annex II specifies:

- Requirements have to be met by the staff and the equipment.
- The maintenance planning.
- The control of the records during the work.
- The quality and safety policy of the organisation must follow the structure of the organisation.

Annex III (Part 66) describes training necessary to acquire the license for Aircraft Maintenance Technician (AMT).[92] Annex IV (Part 147) describes 'how' and 'where' this AMT formation should be taught.[93]

Part 21 lays down the rules governing the airworthiness and environmental certification of an aircraft, related products, parts and appliances, as well as the certification of design and production organisations. A design organisation must hold a Design Organisation Approval (DOA) and provide the design data to a production organisation, which in turn must hold the corresondent Production Organisation Approval (POA). Part 21 specifies the legislation on certification procedures, producing parts and devices, type certificates, requirements for noise emissions approvals parts and systems, individual certificates of airworthiness, flight permits and restricted licenses.

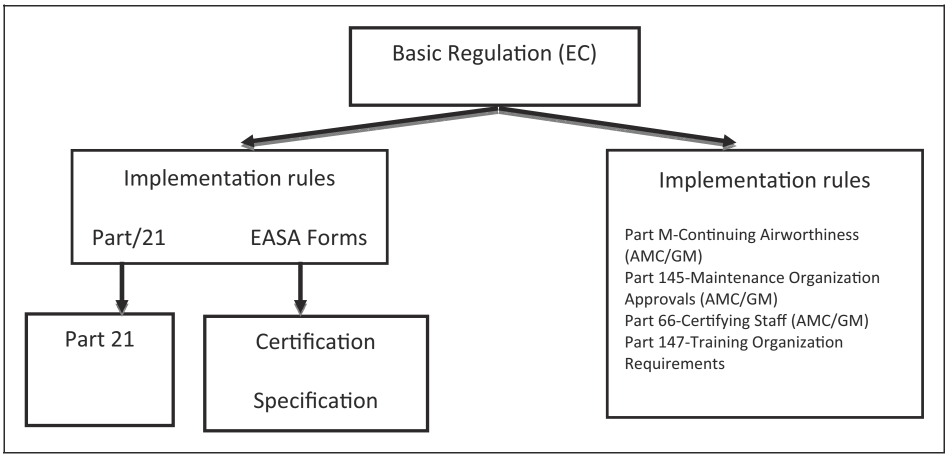


**Figure 6.** EASA Regulations.

As some rules may be subject to interpretation, EASA issues advisory material to explain regulation and, in some cases, suggests suitable procedures to perform a demonstration of compliance with it. The Acceptable Means of Compliance and the Guide Material (GM) are documents that have been issued with each Annex. Figure 6 shows a chart of EASA regulations.

Finally, EASA regulations can be summarised as:

*An aircraft that has been designed by an organization approved under Part-21 may only be operated for commercial air transportation when an operator has hired a maintenance organization that has been approved under Part-145, which uses certifying staff according with Part-66 and they have been trained according with the Part-147.*

## Implementing AM for the aerospace market

The idea of bringing AM into MRO requires meeting European Commission Regulations (regulations related with initial airworthiness, Part 21, and continuing airworthiness Part 145, Part M, Part 147 and Part 66).

A repair or recreation using an AM process has to be developed by an approved design organisation (Part 21, Sub J) or an organisation with comparable capabilities. The introduction of AM as a new production and repair method has to be classified as a major design change (GM 21.A.91)[94] and a major repair (21.A.435(a)).[94] The new process has to be approved (for alternative procedures, see 21.A.14(b)[94]) by national aviation authorities following point 21.A.97 and resulting in approved records that include all relevant data for a specific repair solution.

An MRO service provider with design organisation approval has to approve the new repair design and append a supplemental page (STC) to the applicable Maintenance Manual (GM 21.A.431 (a),[94] 145.B.4[91]) (e.g. Component Maintenance Manual). An original equipment manufacturer (OEM) has to approve the repair solution and include it in the applicable Maintenance Manual (21.A.14 (b) 3.4[94]). A repair solution has to be conducted according to the applicable Maintenance Manual and its amendments. Finally, an EASA Form 1 has to be issued referencing all relevant data.[90]

Traditional manufacturing methods for metallic components have well-established specifications and procedures, and this means that protocols for certifying processes and suppliers are similarly well established. Nowadays, many research efforts are being dedicated by different committees around the world to develop standardisation for AM processes in order to establish the terminology, material and processes and test methods. This will permit AM technology to compete and participate in the aerospace market under the same conditions as conventional manufacturing processes.

## Development of AM standards

The AM industry is starting to respond to the need for standardisation at a global level. As a consequence, various committees with substantial European involvement have been created. The most important ones are the ASTM F42 Committee[95] and the ISO TC 261. Both of them have identified priority topics for standardisation, in particular: qualification and certification methods, design guidelines, test methods for characteristics of raw materials, material recycling guidelines[96,97] and standards protocols for round robin testing standard test artefact,[96–98] requirements for purchased AM parts, harmonisation of existing ISO/ASTM terminology standards[1,66] and testing of finished parts. One of the main challenges of standardisation is the diversity of AM technologies and the need to categorise them accordingly. Some standards have been published and others are in progress, but they still have to be fully assessed and accepted by the aerospace industry and the corresponding aviation authority.

### Conclusions

Unlike other manufacturing processes, AM is neither adequately understood nor characterised to establish a combination of fixed process parameters, acceptance testing, non-destructive inspection, and destructive coupon testing, to confirm if it complies with all requirements. With the current state of this technology in terms of design, qualification, process specifications and standardisation, it is difficult for the aerospace industry to develop a single specification and associated database for AM for a given alloy. In other words, when all variables in the AM process are fixed and the process becomes stable and controlled, the resulting mechanical properties are well characterised and sufficiently invariable, the structural performance of AM parts is predictable using conventional design tools, and the ability to accomplish post-processes is demonstrated (like machining or drilling), then only can AM be considered a viable option in the aerospace industry.

From the point of view of the qualification of AM in the aerospace industry, there are significant challenges because of the following reasons:

- Standardisation is not yet well established. However, the ASTM F42 Committee is working to overcome this challenge. ASTM has issued several standards on AM addressing terminology, file format and the processing of various alloys.

The conventional certification processes for aircraft components is very costly (>$130 million) and lengthy (around 15 years). Thus, new alternative means are needed to accelerate these processes.[99]

- Lack of methods for verifying the key process variables and demonstrating repeatability.
- Need for a clear definition of qualification requirements for each of the three phases of product life cycle, new design/repair and production.
- New advanced NDT techniques capable of detecting critical flaws and defects with a high degree of certainty are needed.

## Discussion and conclusions

Nowadays, EBM, SLM and some MD technologies (like Laser Cladding or WAAM) are widely used as a manufacturing process for metal parts in different industries. But, to implement AM in the aerospace industry, due to the high regulatory framework for ensure the airworthiness, there are many challenges to be reached. Developing new certification concepts and QA/QM processes, which take in account the characteristics of these technologies, will permit reduce time and cost during the manufacturing or repair operations. Although the possibilities of these technologies in terms of cost, speed, reliability and accuracy can be compared in some cases with other traditional manufacturing technologies used in the aerospace sector, further improvements in AM process knowledge and standardisation are required to implement it in the repair and produce operations.

Improvements in new models for AM technologies will permit to achieve better surface quality, dimensional accuracy and process control systems. Thus, the technology can be used for a much broader area of applications, modifying the current aerospace business model.

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### Conflict of interest

None declared.

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Uriondo, Adrian

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